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Reliance of Building Energy in Various Climatic Regions Using Multi Criteria

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Abstract

Selecting a ventilation system for a certain building has always been considered as one of the critical problems for designers. Kingdom of Saudi Arabia (KSA) is characterized by a large area of significant climatic changes. In this research, five criteria are identified to compare and select one of the most popular ventilation systems, mechanical or natural. The identified criteria include Energy efficiency in buildings, Building function, Thermal comfort, the Maintenance cost of building, and Microclimatic conditions. The use of a mechanical system may be useful for achieving the building function and thermal comfort, while it seems to be more expensive. On the other hand, the natural ventilation system saves energy in the long run but it may not meet a comfort level for many users. Three regions which cover most of the climatic variations in the country are selected as a case study. A Ventilation Decision Making Model (VDMM), depends on the Analytic Hierarchy Process (AHP) as a multi-criteria analysis technique, is proposed and developed. For feeding data to the VDMM, field measures for indoor air temperature and relative humidity are conducted as well as applying an energy simulation model to predict indoor energy performance in the selected regions. Based on the results of VDMM application on the investigated case study, a decision to KSA construction market is introduced. The results absolutely support using the mechanical system in both Riyadh and Jeddah regions while utilizing the natural system in Abha region is more preferable. The VDMM is characterized by its flexibility, accepting more alternatives or criteria and its validity to be applied to other regions inside or outside KSA.

Key words: Ventilation system; Decision making; energy saving; sustainable buildings

1. Introduction

Saudi Arabia is considered as one of the largest countries in the Middle East, specifically located in the south-west of the continent of Asia, with an area of about two million square kilometers. It is consisted of deserts with some parts with oases and about half of uninhabitable desert produces a very hot weather type of climate. Most parts of the lands located in the western regions of Saudi Arabia are plateau, lowlands on the east, all producing a very hot weather condition [1].

The weather in Saudi Arabia is composed of extreme aridity and heat. It is among a few numbers of countries in the world where temperatures during the summer period reaches above 50^{o} C. While there can be snow or freezing winter in the higher mountain ranges but this weather event does not happened every year. The average weather temperature during these winter periods are 8^{o}-20^{o} C in areas such as Riyadh and 19°-29° C in places such as Jeddah which is located on the coast of the Red Sea. The mountain regions have the freshest weather condition that is responsible for it to become the greenest part of the entire Kingdom of Saudi Arabia (KSA).

Due to this extreme weather, and the desire to save energy on the long run as well as achieve the thermal comfort and good building function, the selection of a ventilation system became a complex problem in KSA. The selection of a method to ventilate a building in KSA faces another problem, which is the lack of a scientific method or model to select a suitable technique. This process is fundamental and has always been considered as one of the critical problems for designers.

Therefore nowadays, extensive efforts have been directed to support a selection of the alternatives in design. Each technique features many advantages and disadvantages in the selected criteria as will be explained later. Many criteria should be identified to be taken as a base for comparisons. Combining the advantages and disadvantages to compare and quantify the two ventilation system alternatives for the purpose of decision-making is exceedingly difficult. Therefore, the main aim of this study is proposing and developing a multi criteria decision-making model to support the decision makers who design the ventilation systems in a certain region in KSA. The proposed model embraces the broader sense of many criteria. Improving the performance of this method not only increases the benefits of architects but also minimizes cost of building on the long run. Feeding data for the model depends on field survey, field measures and using an energy simulation model in the selected region.

Research methodology

The proposed research methodology for this study can be summarized in the following steps:

1- Identifying the criteria affecting the two ventilation systems, mechanical or natural.

2- Proposing and developing a decision making model (VDMM) that can deal with the problem.

3- Selecting three regions that represent various climatic zones in KSA as a case study.
4- Conducting field measures for indoor air temperature and relative humidity as well as applying an energy simulation model to predict indoor energy performance in the case study regions.
5- Applying the VDMM model on the case study regions using collected data from last step.

Ventilation Systems Alternatives

Ventilation for any building is considered one of the main design concepts. Many reasons oblige designers to ventilate the building such as providing fresh air to occupants, providing natural 'passive' cooling, distributing heating or cooling and dilution and removing pollutants. Two familiar types of ventilation, mechanical and natural, are used in design. Each ventilation system has many advantages and shortcomings. Here is a short description for the two ventilation systems.

Alternative (A): Mechanical Ventilation

A Mechanical ventilation system can be described as the use of heating and cooling load in order to bring the internal condition of the space to the thermal comfort level. People spend most of their time indoors; hence, the reliance on air conditioning system is essential. Moreover, the importance of such system becomes more crucial where the gap between outdoor temperatures swings and the desired indoor comfort become larger [2]. However, there are some other issues in association with air conditioning system such as the existing of sick buildings which suffer from the lack of natural ventilation [3]. There are so many kinds of air conditioning which can be used in buildings. Some of which are quite complex such as central air conditioning system, and others are very simple such as window unit. However, the major purpose of the air conditioning system is transferring the indoor condition into more comfortable environment. This indicates that there is a strong correlation between outdoor condition, indoor and building fabrication. The air conditioning system comes at the end to ensure adequate indoor condition which is affected by outdoor features such as temperature, and building fabrication.

Alternative (B): Natural Ventilation

Natural ventilation is quite associated to cooling purposes, but there are many other purposes for it, one of which is indoor air quality. It has to be mentioned that even in cooler regions where there is no need for natural ventilation as a cooling method, there should be at least a minimum of air-exchange with external environment to release the contaminated air indoors ([4], [5], and [6]). There are many types of natural ventilation and the most common techniques as follows: creating positive and negative pressure inside the building ([6] and [7]), outside techniques ([7] and [8]) and Stack driven pressure [8]. It may be hard to apply natural ventilation in hot and humid regions due to extreme of outdoor environment, but there should be some possibility during night and in winter when outdoor temperature drops close to or even lower than indoor thermal comfort.

Analytic Hierarchy Process (AHP) model

The AHP was developed by Saaty 1980 [9] to solve decision making problems prioritization of decision alternatives and widely used in decision making systems. AHP has been implemented in construction projects decision making and risk assessment to solve many problems ([10], [11], [12] and [13]). AHP uses actual measures like price, counts, or subjective opinions as inputs into a numerical matrix. The outputs include ratio scales and consistency indices derived by computing eigenvalues and eigenvectors. The AHP models decision making framework that assumes a unidirectional hierarchical relationship among decision levels [14]. The hierarchical approach allows AHP to investigate the interrelationships amongst sustainability criteria. This is important as the various aspects and criteria pertaining to sustainable development are often linked together [15].

In this work, an AHP model is introduced, as it is offered a logical and representative way of structuring the decision problem and deriving priorities. The main purpose of this model is giving support for selecting a ventilation system from mechanical or natural. After arranging the problem in hierarchical terms, a calculation for relative importance of each identified criterion, using a pairwise comparison technique [16], is done and applied for the five identified criteria. For example, many questions can be asked to the decision makers such as “How Important is criterion 1 when it is compared to criterion 2". The second level of questions combined the five criteria interchangeably and the choice of using natural or mechanical system. An example of a question in this such as "How important is criterion 1 when it is compared to the use of mechanical system or the use of natural system". The model consists of one matrix in the first level and 5 matrices in the second level. The comparisons are done by utilizing the preference scale [9]. The pairwise comparisons from each branch at each level of the hierarchy are entered into a matrix and used to determine a vector of priority weights. The decision maker should choose a defined number from 1 to 9 to perform pairwise comparisons on the elements. The nine-point scale can be defined as: 1 refers to "equal importance", 3 refers to "somewhat more important", 5 refers to "much more important", 7 refers to "very much more important", and 9 refers to "absolutely more important". The consistency ratio (CR) is calculated as a measure of cognitive effort in the decision which is calculated as follows:

$$CR = CI \backslash RI$$

Where: (CI) is consistency index and (RI) is relative importance or eigenvector [9].

Criteria identification

The brainstorming is one of the most common identification techniques for data collection in construction industry [12]. To satisfy the research objectives, a brainstorming session is organized at Taif University, KSA. This session was conducted to identify the criteria affecting the two alternatives. The session was carried out with two architectural professors, two research team members, two architectural designers, and one consultant of electro mechanical systems. All attendees possess practical experiences in ventilation systems and architectural design.

As a result from this session, five criteria were identified as having impacts from a theoretical perspective and become the theoretical foundation for the proposed Ventilation Decision Making Model (VDMM). The results from the brainstorming session was designed to address the decision making process for ventilation system selection. The data required to feed the model included data collection about the five criteria and model application for climatic conditions in the selected regions. The five criteria include:

Criterion (01): Energy efficiency in buildings
Buildings are responsible for at least 40% of energy use in most countries [17]. There are several strategies which can make a building more sustainable and energy efficiency, which produce less amount of energy in order to achieve thermal comfort for the users. Energy performance in buildings has many advantages such as increase asset value, reduce energy costs, improve the operating performance of the building, and the most important advantage is enhancing the comfort of building's occupants.

Criterion (02): Building function
Buildings have been classified based on their function to seven types as follow [18]: residential, office, commercial, industry, education, health and hotel. However, other researchers may classify buildings into narrower classifications to include residential, office, health and education [19]. Considering the amount of heat gain produced from indoor environment from all these buildings can have a major influence on the total energy required to bring the indoor temperature to the thermal comfort level. For instance, heat produced from a classroom in a school which has more than 20 students cannot be compared with a domestic space which has a family with about 3-5 users. This can explain the over-heat in large halls. Consequently, engineers and architects have to take this into consideration in order to provide a more thermally acceptable environment which consumes less amount of energy.

Criterion (03): Thermal comfort
Thermal comfort can play an important role in human performance at both physical and mental levels [19]. There are two main strategies in order to estimate thermal comfort for users ‘Predicted Mean Vote’ (PMV) and also the Percentage of Dissatisfied (PPD) [20]. These approaches are based on Fanger’s investigation which bear in mind some environmental aspects such as dry bulb temperature, humidity, air velocity and mean radiant temperature as well as human factors such thermal resistance and metabolic rate [21]. Thermal balance is copied when the internal heat production in the body is equal to the heat loss to the surrounding environment (ISO 2005). An abounding publications investigate and validate these methods worldwide.

However, there were many results which against them, but they still have a good contribution to be the most commonly used approaches [21]. PMV in abundant publications was found to be misguiding when compared to present state of thermal comfort [22, 23]. It works more accurate in the operation of air conditioning. However, adaptive comfort models tend to have wider range of comfort temperatures. Thus, it will have considerable amount of energy consumption.

Criterion (04): Maintenance cost of building

Maintenance cost is considered a part of the building's life cycle costs. The whole life cycle costs consist of non-construction costs, incomes, and life cycle costs (Construction, maintenance and operation costs plus any residual value) [24]. The Key factors that impact the level of maintenance cost may include quality of materials and components in buildings, quality of designs and workmanship in construction in addition to wear associated with usage/occupancy. The maintenance cost may cover condition assessment, statutory maintenance, preventative maintenance, and unplanned maintenance costs.

Criterion (05): Microclimatic conditions

A microclimate is a local set of atmospheric conditions that differ from those in the surrounding areas, often with a slight difference but sometimes with a substantial one. Both weather and climate are characterized by the certain variables known as climatic factors [25]. They are as follows: (A) Solar radiation (B) Ambient temperature (C) Air humidity (D) Precipitation (E) Wind (F) Sky condition. More details of this criterion will be explained later.

The Case study

The investigated case study in this research is selecting and supporting the ventilation system in three regions in KSA (Riyadh, Jeddah and Abha). The locations and geographical topography of the investigated regions are shown in Fig.1. Although the dominant climate in Saudi Arabia is hot and dry, there is a variation in the local climate of each region. Generally, the climate can be classified into three main variations; (1) Hot and dry which is representing the majority of the country; (2) Hot and humid along the East and West cost of the country and (3) Moderate climate for the higher land mountains located at the South-West of the county. As shown in fig.1 the three studied regions are selected to cover all climate variations in the country. Riyadh represents hot and dry and Jeddah illustrates hot and humid while Abha represents moderate of high land climate.

The field measures were executed on three school buildings. School buildings are selected due to their major role in defining students' achievement. Consequently, students should be comfortable during their school activities. Moreover, energy efficiency, indoor air quality and thermal comfort conditions are considered the leading factors that have an influence on school buildings [26, 27, 28]. Some other elements make thermal comfort considerations in schools substantial is maintaining the capability of students, while discomforting may lead to the opposite effect. The literature on school buildings design is enormous with high considerations on architecture in relation to education theory [29, 30]. There are limited publications about schools in terms of thermal performance and comfort. This is more apparent in hot regions. Most of the works concerning indoor thermal comfort has been conducted in offices and domestic buildings [31].

Selected school buildings characteristics

The selected school buildings have been designed to comprise three levels of general education which are primary, secondary and high schools. However, it seems that the staff in the school is not happy with that. This was clear through site observations and meetings with students and staff of the schools. In general, there is an obvious lack of space associated with this design. Furthermore, a large area has been taken for parking which represents about 40%. Primary level was given two blocks of the school, whereas the secondary and high levels were given one block for each. This is due to the number of academic years in each level (six in primary level, three in secondary level, and three in high school level). The selected schools have a unique design with a fan shape as shown in fig. 2. Consequently, there is no major impact of changing the orientation of the school. For instance, in the case of trying to control the sunlight from one block, the other will receive the same impact.

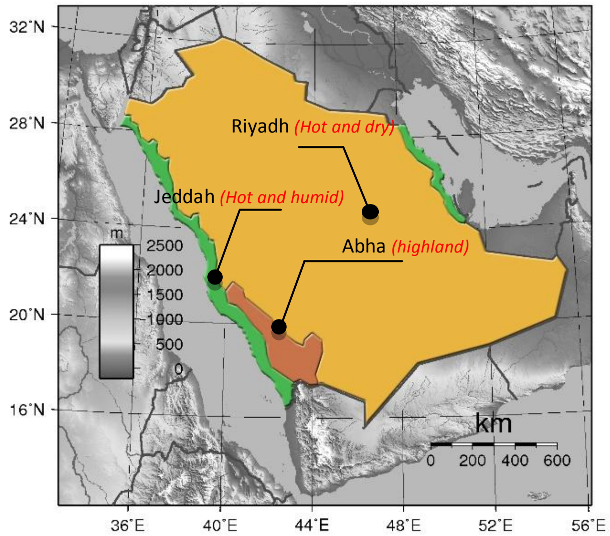

Fig.1 the locations and climatic variations represented by the three selected regions [26].

Field Measures for Indoor Air Temperature and Humidity

The use of equipment to measure the environmental parameters is an important method in this research for the purpose of feeding the proposed model. The research intends to measure indoor dry bulb temperature, outdoor dry bulb temperature, indoor relative humidity, outdoor relative humidity, indoor air velocity, outdoor air velocity, indoor globe temperature and temperature of internal inner surfaces for selected three buildings (schools) with the same architectural plans but located three cities regions (Riyadh, Jeddah and Abha). Fig.2 shows a plan for the schools and a photo taken in Jeddah. The intervals selected for measurement are at 5:00 am, 8:00, 11:00 am and 2:00 pm. The reason for these periods is to ensure the time of minimum and maximum temperatures which represent the extremes of the outdoor conditions and its implementation on the internal status. In addition, the time specified of 11:00 am was the only time of conducting the survey. Consequently, it was essential also to look at the internal conditions in order to compare the results.

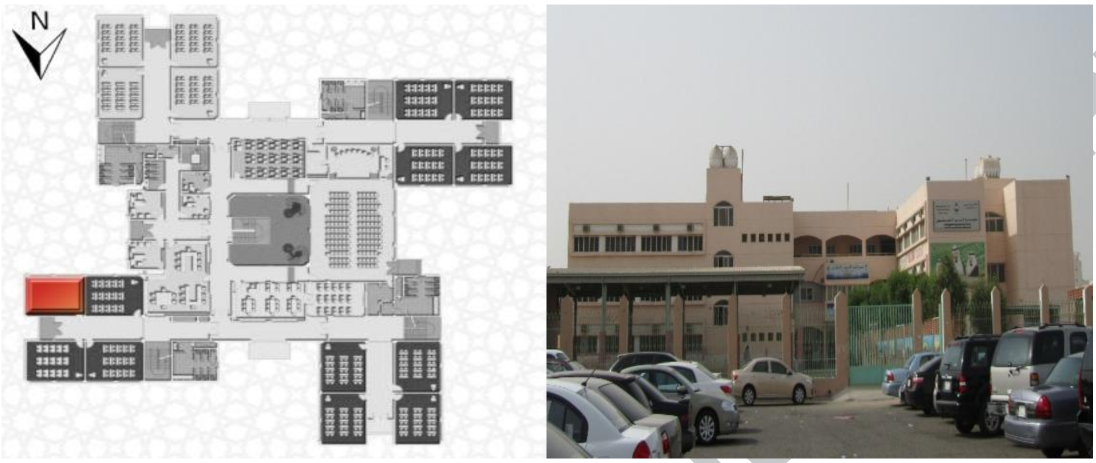

Fig. 2 a plan for the schools in the three cities and a photo taken in Jeddah

There was an issue regarding the accuracy of the measurements taken and the use of Air Conditioning (AC) system. This problem was solved at the time of 5:00 am and 2:00 pm since all the classrooms are unoccupied, hence, there was no need for cooling load. However, an issue has been revealed at the time of conducting the survey (11:00 am). It was not possible to turn off the AC system all day as the schools rely heavily on the cooling system due to the harsh condition outdoors as well as the poor design of the new prototype school building, which has no consideration for any environmental design. This has contributed to unacceptable internal conditions even in winter. It is expected to obtain the same results derived from the two different methods. This is why it was not possible to conduct the study at the weekends. However, weekends where used to set up data loggers only in order to investigate the pattern of 24 hours in the complete absence of AC system for as many of the classrooms in the schools as possible.

Fig.3 shows the tools used in field measures for site observations. It is clear that some of the regions have a free running system in order to provide more comfortable indoor environment. The city of Riyadh (hot and dry climate) was found with the largest temperature swing between day and night time, and also between summer and winter, where temperature swing between summer and winter was as high as 15 C°. In contrast, the city of Jeddah (hot and humid climate) had a quiet little fluctuation in comparison with the city of Riyadh with less than 5C° of average day time temperature. Similarly, the city of Abha (moderate climate) had a similar pattern compared to Jeddah with much lower temperatures. Fig. 4 to fig. 6 shows the measurements results of indoor, outdoor, globe, floor inner surface and roof inner surface temperatures of the selected buildings in summer in the three regions.

Fig.3 Tools used in field measures in site observations where:

A: TECPEL professional Hot Wire Anemometer
B: CEM Dual Laser Infrared Thermometer
C: CEM USB Temperature and Humidity Data logger
D: Globe thermometer
E: Tecpel thermo hygrometer

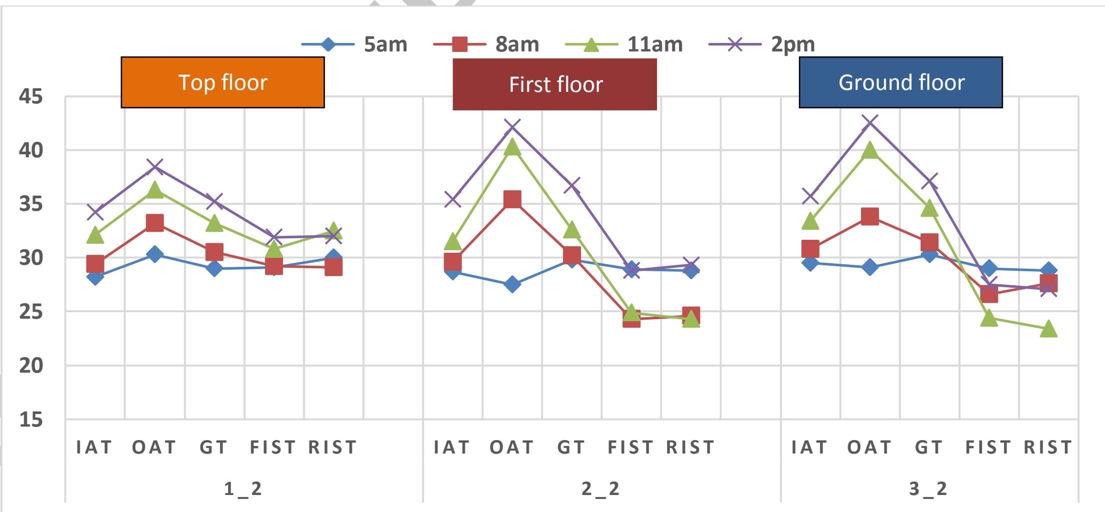

Fig.4 Indoor, outdoor, globe, floor inner surface and roof inner surface temperatures of the selected building in summer, Riyadh city where:

IAT: Indoor air temperature
OAT: outdoor air temperature
GT: global temperature
FIST: floor inner surface temperature
RIST: roof inner surface temperature

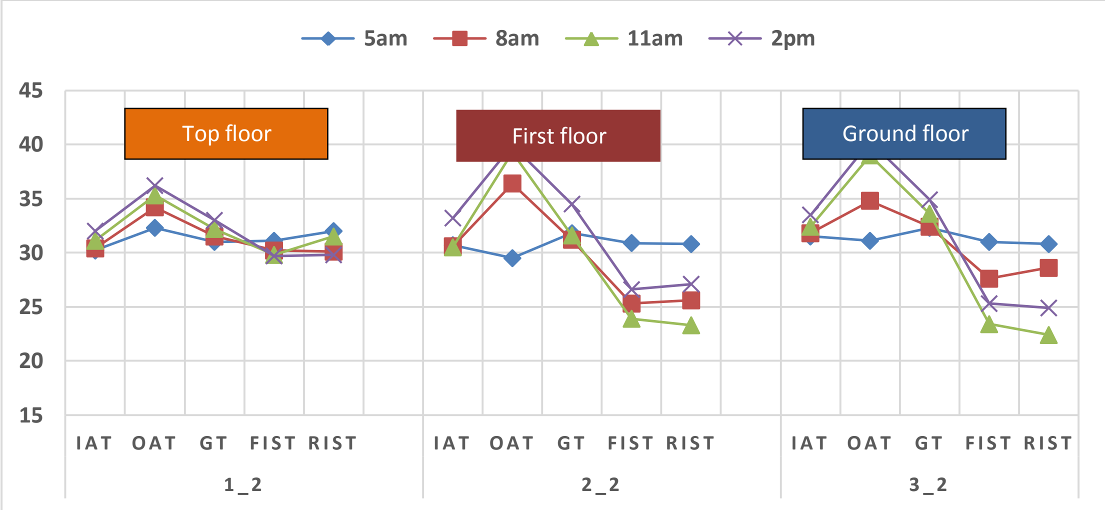

Fig.5 Indoor, outdoor, globe, floor inner surface and roof inner surface temperatures of the selected building in summer, Jeddah city

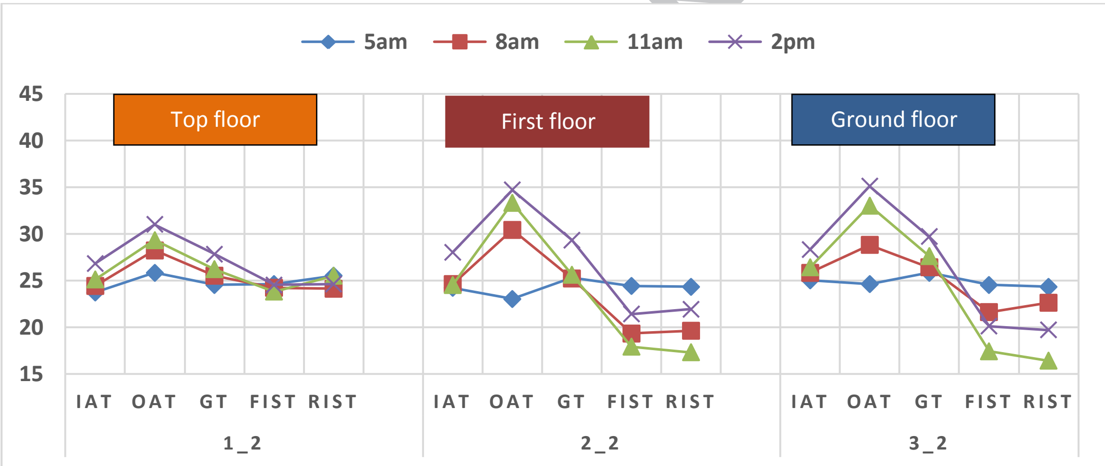

Fig.6 Indoor, outdoor, globe, floor inner surface and roof inner surface temperatures of the selected building in summer, Abha city

Building energy performance determination

One of the main objectives in the present work is to apply an energy simulation model that commercially named (TAS). This Software is developed by Environmental Design Solutions Limited (EDSL) in 1989. It is considered as one of the most common used tool to predict building energy performance [32]. The TAS version (9.3.3) with the license number of (NW3P-BWHW-QX6K-IQHX) is used to predict indoor energy performance of buildings including dry bulb temperature, relative humidity, solar radiation surface temperature and much more. Fig. 7 to fig.10 shows the results generated from the development of this model.

In order to investigate the performance of the three regions more precisely, the aid of natural ventilation was involved in both summer and winter in order to establish its impact (fig. 7 and fig. 8). Based on the thermal comfort identified in fig.7, the city of

Abha is the closest region to climate zone in winter and summer. The city of Riyadh is very close to the comfort zone in winter, however, it is significantly discomfort in summer. The region of hot and humid climate (Jeddah) has its summer comfort at the upper level of the comfort while, the summer performance is the second behind the pattern of Riyadh. One of the reasons why Abha city has a quite pleasant weather condition all over the year, is the amount of solar radiation which can be seen in fig.9. In both summer and winter the maximum amount of solar radiation has not exceeded 1500W whereas it was above 2500W in the other cities, Jeddah and Riyadh.

All these characteristics were clearly reflected on the amount of heating and cooling loads (fig.10). The city of Riyadh has the largest amount of cooling load which is almost 200000W, the city of Jeddah came behind with about 180000W. On the other hand, the city of Abha has only 80000W in summer in order to cool the space. On top of that, the city of Jeddah requires more energy in winter to cool the building than in Abha in summer. Such results indicate the importance of energy required in each region in order to maintain thermal comfort at expectable level.

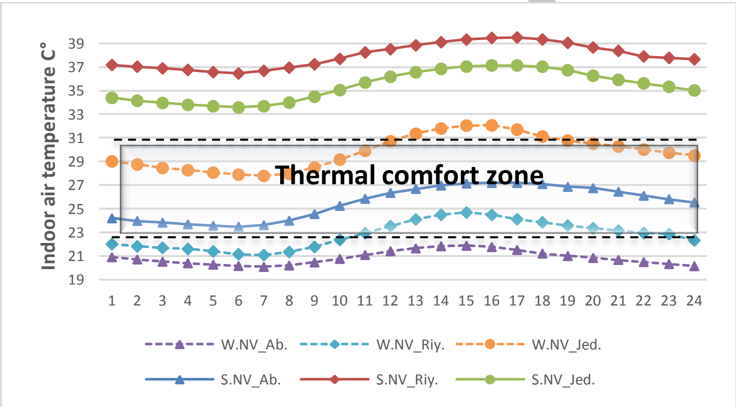

Fig.7 IAT in various climatic regions with free running system

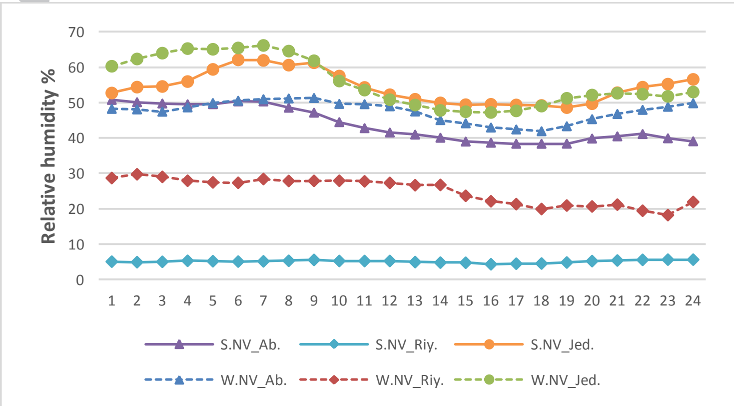

Fig.8 RH in various climatic regions with free running system

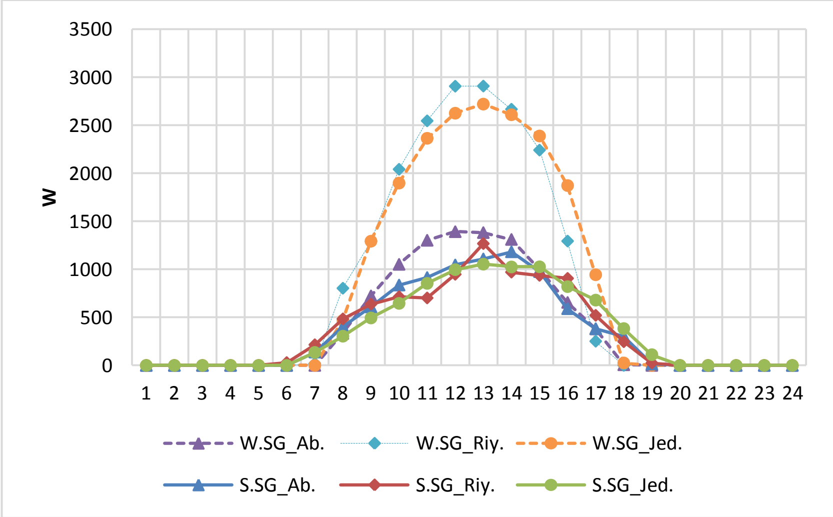

Fig.9 solar heat gain, W

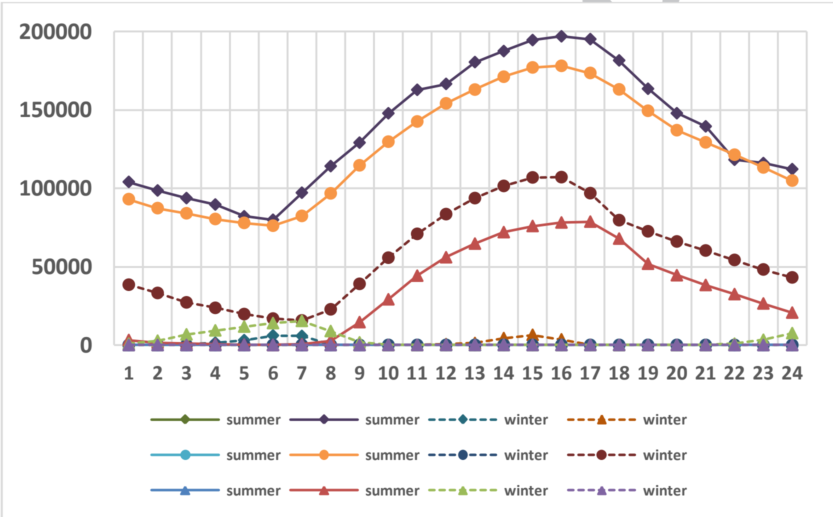

Fig.10 Heating and cooling loads in all climatic conditions (summer and winter)

Application of Ventilation Decision Making Model (VDMM)

A brainstorming session is conducted with major construction project stakeholders for the purpose of data collection to feed the model. This step was done by a question and answer session to make sure that everyone fully understood each response. All attendees were informed by the objective of the session for enhancing its efficiency. A detailed presentation includes all results of the field measures as well as the results coming from application the simulation model for building energy performance. These results are deeply discussed in the beginning of session. Regarding the VDMM, several comparison matrices are introduced and explained. The goal of the analysis is to support the choice for one of the available two ventilation systems to be used in the study area. The five identified criteria are explained for the attendees and they have asked which of them have the same effect on the two ventilation systems and why they have different effects.

Results and discussion

Tables 1, 2 and 3 show the resulted comparison matrices in the three regions, Riyadh, Jeddah and Abha respectively.

Table 1 The comparison matrix for the selected criteria in Riyadh Region

Items	Cr-01	Cr-02	Cr-03	Cr-04	Cr-05
Cr-01	1	1	0.2	3	0.2
Cr-02	1	1	0.2	3	0.2
Cr-03	5	5	1	7	1
Cr-04	0.334	0.334	0.143	1	0.143
Cr-05	5	5	1	7	1

Table 2 The comparison matrix for the selected criteria in Jeddah Region

Items	Cr-01	Cr-02	Cr-03	Cr-04	Cr-05
Cr-01	1	1	0.2	3	0.334
Cr-02	1	1	0.2	3	0.334
Cr-03	5	5	1	5	3
Cr-04	0.334	0.334	0.2	1	0.2
Cr-05	3	3	0.334	5	1

Table 3 The comparison matrix for the selected criteria in Abha Region

Items	Cr-01	Cr-02	Cr-03	Cr-04	Cr-05
Cr-01	1	0.2	0.2	1	0.143
Cr-02	5	1	3	3	0.334
Cr-03	5	0.334	1	3	1
Cr-04	1	0.334	0.334	1	0.2
Cr-05	7	3	1	5	1

The Consistency Ratio (CR) was found to be 2.1%, 4.6% and 8.90 %, in Riyadh, Jeddah and Abha respectively. All consistency ratio values are less than 10% which represent consistent matrices. This may refer to that the selections in matrices were very clear to attendees. The best selected matrix was for Riyadh region because it has the lowest CR value, while, the worst one was for Abha region.

For the second level, there are 5 matrices as explained before. The collected data for Riyadh concludes that the mechanical system is "much more important" for criterion 2 , and "very much more important" for criteria 3 and 5, while the natural system is "much more important" for criteria 1 and 4. On the other hand, the summary of data collection for Jeddah concludes that the mechanical system is "much more important" for criteria 2 and 3 and "somewhat more important" for criterion 5, while natural system is "much more important" for Criteria 1 and 4. Finally, the collected data for Abha concludes that the mechanical system is "much more important" for criterion 2 and "somewhat more important" for criterion 3, while natural system is "very much more important" for the remaining criterion 1, 4 and 5.

The final results from applying the VDMM are summerized in fig.11. The model results proved that the use of natural system in Abha region is supported by a percentage of 54.2% versus a percentage of 45.8 % for using mechanical system. On the other hand, the model supported using mechanical system in both Riyadh and Jeddah regions by 77.6 % and 70.50% respectively. The Final decisions from model results are summarized in fig. 11.

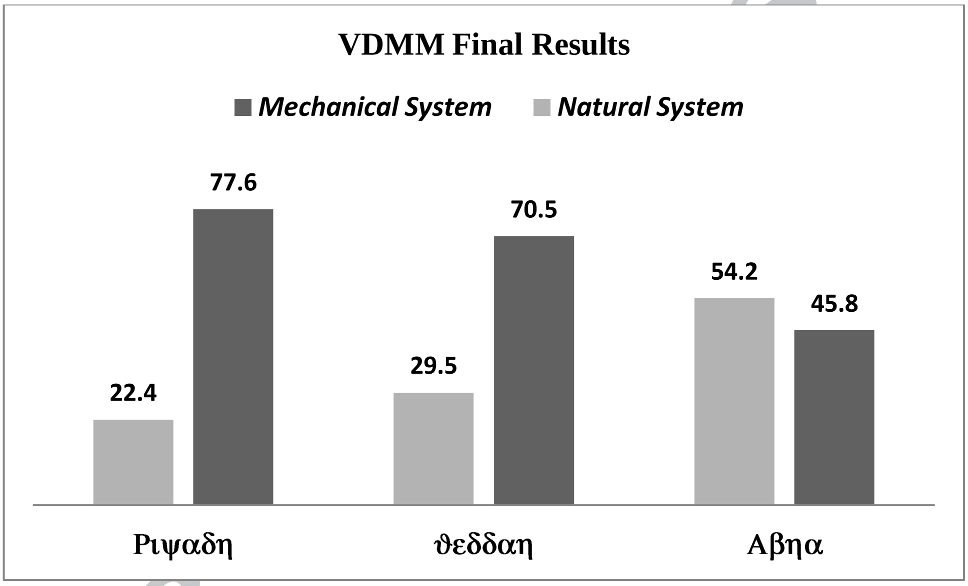

Fig.11 shows the final results of the model in three regions

It seems that both microclimatic conditions and thermal comfort criteria in the city of Riyadh have attributed to control the decision, which supports the selection of mechanical system. This may be comprehensible due to the excessive conditions in this city which is extremely hot in summer and cold in winter. The issue of considerably high outdoor temperature is not the only problem in this weather, but lack of humidity makes it very difficult to treat with the internal conditions. In addition, in order to make the indoor space more comfortable, the mechanical system has to be integrated. Otherwise, the space would suffer from discomfort. In Jeddah city, a comparative result is obtained for using mechanical system. This is controlled by thermal comfort criterion followed by microclimatic conditions criterion. Although the outdoor temperature were also relativity high in this city, higher humidity aids to bring the thermal comfort into more acceptable level with the utilization of natural ventilation. The rise in the air speed helps in decreasing the heat out of the skin by convection heat transfer. Since the city of Abha has high relative humidity with moderate outdoor temperatures, it relies more on natural system rather than mechanical ones.

Conclusions

The main aim of this paper is developing and applying a multi criteria decision making model to quantify the selection of an appropriate ventilation system for a building in a certain region. The methodology used in this research included identification and using five criteria as a base for comparing mechanical or natural ventilation systems. The proposed model (VDMM) is developed using the concepts of AHP. The reasons for using the AHP are due to the usage and addressing the complex systems and selecting the best alternative. VDMM depends on weighing alternatives and selected criteria based on many relationships among them through many decision levels. The methodology included also conducting a field survey for the purpose of data collection to feed the model. In addition, field measures and a simulation model for indoor air temperature and relative humidity for microclimatic conditions in the selected regions are conducted. The VDMM which developed and used is considered the main finding in this study. It is suitable for other case studies inside or outside KSA and it can be adopted for that. The number of criteria and alternatives can be simply modified.

Based on the results obtained in this study, the specific conclusions can be drawn as follows:

1-Three regions in KSA are selected to cover most climate variations in the country which are; (1) Riyadh (Hot and dry), (2) Jeddah (Hot and humid) and (3) Abha (Moderate climate).

2- The Field measures introduce the indoor, outdoor, globe, floor inner surface and roof inner surface temperatures for the buildings in the selected regions.

3-The application of the simulation energy model (TAS) provides the indoor air temperature and relative humidity as well as it identifies the thermal comfort in the selected regions. The solar radiations and heating and cooling loads are also determined for the case study area.

4-The results of the VDMM proved that the use of natural system is better compared to the use of mechanical system in Abha region. On the contrary, the mechanical system is better in Riyadh and Jeddah regions.

5-Using natural system in Abha is supported by about 17% only over using the mechanical system, while in Riyadh and Jeddah; the mechanical system is supported by 240% and 138 % respectively over using natural system.

Finally, as a recommendation for further research, and for the reason of energy-saving, it is suggested to explore and improve new methodologies that can be implemented and combining the natural ventilation with mechanical system in Riyadh and Jeddah regions.

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